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The AFOSR Optoelectronics Research Center at the University of New Mexico has continued its aggressive, broadly ranging program. Novel InGaAs and AlGaAs device structures such as resonant-periodic-gain surface-emitting lasers and high-power, coherent unstable resonator wide-stripe lasers have been pioneered. Processing advances have included investigation of III-V regrowth over patterned wafers allowing unique device structures such as unstable laser arrays, and the extension of interferometric lithography techniques has led to the definition of Si quantum wire and dot structures. Process technology improvements such as GaS passivation have extended the catastrophic optical breakdown limits of GaAs lasers. External cavity operation of diode lasers has provided information on internal device physics and on the fundamental limits of laser characteristics. Self-consistent thermal, electrical and optical modeling of both single-element and array geometries has led to improved device performance. A major advance is the coupling of phototransistors with surface-emitting lasers to make "smart pixels." Data rates for HBT/VCSEL switches as fast as 500 Mb/s have been demonstrated. Upconversion fiber lasers have been developed for the green (Er-doped ZBLAN) and blue (Tm-doped ZBLAN). Confocal photoluminescence spectroscopy has been developed as a simple, sub- μ m spatial resolution tool for the study of regrown structures.

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I. Introduction

The *Optoelectronics Research Center* (OERC) at the University of New Mexico that was begun in FY87 under the auspices of the Air Force Office of Scientific Research, has functioned in conjunction with the *Center for High Technology Materials* (CHTM), which is being supported by the State and University of New Mexico, with the *Optoelectronic Materials Center*, which is being funded by DARPA. CHTM is an interdisciplinary research organization with faculty and research representation from four departments: Electrical Engineering, Physics, Chemistry and Chemical Engineering. We anticipate that the effectiveness of the AFOSR OERC will be enhanced by the infrastructure already in place at CHTM as well as by the resources of the related DARPA programs. Since its inception, the AFOSR OERC has become a leading university optoelectronics program with substantial impact on the development of the field.

The goal of the AFOSR OERC is to continue to be at the forefront of advances in optoelectronics. The coupling and increasing merger of optics and electronics has already had important consequences, but the major advances which will occur over the next decade will dwarf those seen to date. These will result from advances in linear and nonlinear materials, device processing, device design, and in device integration. Examples of materials and structures are quantum wells, superlattices, strained-layer semiconductors, and new nonlinear materials. Processing developments relate to smaller dimensions and improved techniques for the selective deposition, modification and removal of materials. Improved devices also result from increased understanding of the underlying device and material physics and from innovative approaches to device design and synthesis. Integration of multiple optical functions and between optical and electronic functions will have an increased impact.

The AFOSR OERC has produced significant results in all of these areas. Highlights are provided in the next section. In III-V materials and structures, novel InGaAs and AlGaAs device structures such as resonant-periodic-gain surface-emitting lasers and high-power, coherent unstable resonator wide-stripe lasers have been pioneered. Processing advances have included careful investigation of III-V regrowth over patterned wafers that allow unique device structures such as unstable and leaky-mode laser arrays, and the extension of interferometric lithography techniques that have led to the definition of isolated and passivated quantum wire and dot structures in Si. Process technology improvements such as GaS passivation have extended the catastrophic optical breakdown limits of GaAs lasers. External cavity operation of diode lasers has provided a wealth of information on internal device physics and on the fundamental limits of laser spectral and temporal characteristics. Self-consistent thermal, electrical and optical modeling of both single-element and array geometries has led to improved understanding and device performance. A major advance in integrated structures is the coupling of phototransistors with surface-emitting lasers to make "smart pixels" that can operate in parallel on an array of optical signals. Data rates for HBT/VCSEL switches as fast as 500 Mb/s have been demonstrated. Upconversion fiber lasers, using our high-power GaAs laser technology, have been developed for the green (Er-doped ZBLAN) and blue (Tm-

doped ZBLAN). Confocal photoluminescence spectroscopy has been developed as a simple, sub- μm spatial resolution tool for the study of regrown structures. We have developed a novel "see-through" device design that, for the first time, allows direct observation of filamentation in high power diode lasers.

An important driver for the success of the AFOSR OERC program is the vertical integration of capabilities within CHTM. These extend from semiconductor and nonlinear materials growth and characterization, through fabrication and processing, to device synthesis, characterization and integration. The juxtaposition of these resources within a common research setting provides an important cross-fertilization that is crucial for rapid progress in this multidisciplinary area.

Interaction with Air Force personnel and research and development programs and needs is a major aspect of this AFOSR OERC. Particularly close relations are maintained with the Air Force's Phillips Laboratory programs in diode lasers (PL/LIDA), nonlinear optics (PL/LIDN), and active (PL/VTRA) and passive (PL/VTRP) space-based sensors. Strong ties are also maintained with the Rome Laboratory programs in photonics.

II. Technical Accomplishments during 1992-1995 Program

High Power, Coherent Semiconductor Lasers:

- Diffraction limited operation of the RLT laser at a total power in excess of 1 W CW;
- Development of a novel "see through" CW laser allowing the direct observation of filament behavior under high power CW operation;
- Development of a high resolution 2D thermal mapping technique for the study of thermal focusing under high power CW operation;
- Development of MOCVD technology for a novel "all epitaxial" version of the SHUR laser;
- Achievement of 770 mW pulsed output from the PHOTO-SHUR laser with high coherence;
- Single-frequency, high-power (~2 W) diode laser, tunable from 960-980 nm, using an unstable-resonator flared-amplifier in an external-cavity configuration;
- Demonstration of a picosecond high-power diode laser using a multiple-contact unstable-resonator flared-amplifier in an external-cavity, by using mode-locking technique;
- Development of a spectroscopic measurement system based on the delayed-self-heterodyne technique.

High-Power Diode Laser Arrays:

- Development of coupled broad-area mode theory of gain guided diode laser arrays;
- Explanation of high-order array mode structure in gain-guided laser arrays.

Process Technology for High-Power Diode Lasers:

- Demonstrated 50% increase in catastrophic optical damage limit in diode lasers coated with GaS passivation;
- Showed reduction in mirror facet heating of diode lasers using GaS passivation resulting in increased reliability;
- Developed self-aligned contact process using ECR-based RIE for ridge waveguide diode lasers.

Electromagnetic Induced Transparencies in Semiconductor Quantum Wells:

- Development of single electron formalism for multi-field quantum electronics in semiconductors;
- First observation of Rabi splitting/optical Stark effect at room temperature in undoped quantum wells;
- Design of induced zero absorption and gain without inversion structures.

Dynamics of External-Cavity, Single-Mode, Edge-Emitting Lasers:

- Explanation of the important role of intrinsic resonances of lasers in chaotic behavior;
- First observation of the period-doubling route to chaos;
- Confirmed the deterministic nature of chaotic behavior by dimensionality analysis;
- Discovered the importance of the intrinsic resonance frequency on chaos;

- Extended the understanding of chaotic lasers to modulated oscillators.

Injection Locking of Edge-Emitting Diode Lasers with Phase Conjugate Feedback:

- Demonstrated two uncoated edge-emitting laser diodes in a master/slave relationship via a photorefractive double phase conjugate mirror;
- Demonstrated side mode phase conjugate injection locking up to nine longitudinal modes;
- Measured asymmetric stable locking range;
- Measured instabilities caused by phase conjugate feedback.

Side-Mode Injection Locking of Semiconductor Lasers:

- First comprehensive analysis of side-mode injection locking including noise effects;
- Theoretical prediction of ultrafast wavelength switching using side-mode injection locking.

High-Power Resonant-Periodic-Gain Surface-Emitting Lasers:

- Invention of a new distributed-feedback resonant-periodic-gain (DFB-RPG) surface-emitting laser structure;
- Design and fabrication of first DFB-RPG GaAs/AlGaAs/AlAs lasers;
- Demonstration of record-high output power density from optically pumped DFB-RPG laser.

VCSEL Optimization and Integration:

- Achieved record low series resistance ($12\ \Omega$ for a $26\ \mu\text{m}$ diameter device), and very wide temperature range of operation (500°C pulsed, 300°C cw);
- Modeled the high speed performance of VCSELs obtaining a modulation bandwidth of close to 10 GHz, and determined a maximum intrinsic bandwidth of 44 GHz;
- Achieved efficient VCSELs (14% power efficiency) with high optical power and thermally stable electrical characteristics;
- Experimentally studied the parameters governing the temperature dependence of the VCSEL's electrical and lasing characteristics leading to design rules for optimizing VCSEL performance over any temperature range, including cryogenic applications;
- Designed and implemented monolithic integration of VCSELs with HBT technology;
- Measured and modeled the modulation response of the HBT/VCSEL switches, and demonstrated operation at a data rate of $> 500\ \text{Mb/s}$.

Stable Phase Locking and Instabilities of an Electrically Pumped VCSELs:

- Achieved stable phase locking of VCSELs by direct injection of a master laser;
- Obtained linewidth enhancement factor α from asymmetrical locking;
- Observed and modeled the dynamic behavior of optical injection.

External-Cavity, Resonant-Periodic Gain, Surface-Emitting Lasers:

- First cw operation of an external-cavity surface-emitting laser;
- Fundamental studies of polarization and frequency selectivity.

Thermal Analysis of Vertical-Cavity Surface-Emitting Lasers and 2-D Arrays:

- Development of self-consistent thermal-electrical analytical model of etched-well VCSELs with dielectric mirrors;
- Optimization of solitary device design for maximum cw output power;
- First analysis of thermal crosstalk in 2-D VCSEL arrays;
- Development of self-consistent thermal-electrical analytical model of proton-implanted top-surface-emitting lasers (PITSELs);
- Development of approximate analytical techniques for calculating thermal resistance of VCSELs;
- Worldwide leadership in comprehensive thermal modeling of VCSELs and 2-D arrays.

Fundamental Studies of Low-Dimensional Optoelectronic Structures:

- Systematic study of operator ordering at abrupt interfaces in quantum wells and superlattices;
- Correspondence principle formulation of density of states in finite-barrier quantum wells.

Optical Properties of Si Nanostructures:

- Fabrication technologies developed for large area, inexpensive production of sub-10 nm quantum wall and wire structures;
- Electromagnetic Raman enhancement ($100\times$) for $\sim\lambda/2n$ wall structures;
- Raman lineshape asymmetry and splitting for $\sim 5\text{-}15$ nm wide wall structures;
- Visible photoluminescence for sub-10-nm structures;
- Visible photoluminescence from quantum wire structures;
- Demonstrated importance of periodic-structure leaky modes for both Raman and photoluminescence results.

Upconversion Fiber Lasers:

- Green (544 nm) upconversion fiber laser in Er-doped ZBLAN fibers with 40 mW output and $\sim 50\%$ slope efficiency, pumped by Ti-sapphire laser at 971 nm;
- Demonstration of a novel wavelength-shifted (1140 nm) pump fiber laser with >1.5 W output, using Raman shift in a standard fiber;
- Preliminary investigations of a blue (480 nm) upconversion fiber laser in Tm-doped ZBLAN fiber, pumped using the above Raman fiber laser;
- Investigation of co-doped ZBLAN glasses, e.g. Tm & Nd, etc., for developing efficient laser transition.

Single-Polarization Fiber Lasers:

- Demonstration of a simple single-polarization fiber laser in Nd-doped elliptical-core silica fibers with ~ 10 dB polarization extinction, without the use of any polarization selective element in the cavity;
- Experimental investigation and modelling of gain-anisotropy in rare-earth-doped elliptical-core fiber amplifiers and lasers.

Confocal Photoluminescence Spectroscopy:

- Demonstrated $< 1\text{-}\mu\text{m}$ spatial resolution for semiconductor photoluminescence;
- Developed simple, non-contact diffusion length measurement;
- Applied to understanding of growth over non-planar surfaces.

Second-Order Nonlinearities in Silica Materials:

- Dynamics of nonlinearity growth in bulk materials;
- Temperature, voltage, multiple poling studies to elucidate physical mechanisms;
- Extension to waveguide thin-films on Si substrates;
- Demonstration of high-temperature hydrogen loading;
- Extension to ultraviolet laser induced poling;
- Electrooptic effect in poled optical fiber.